

CRH SSD
FEBRUARY 1993

CENTRAL REGION TECHNICAL ATTACHMENT 93-04

EFFECT OF WIND AND TEMPERATURE ON HUMANS - REVISITED

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1. Introduction

Ever since WSOM Chapter C-42, Winter Weather Warnings, and its accompanying ROML, C-01-93, were issued, we have received a number of inquiries regarding wind chill and our susceptibility to frostbite i.e., the freezing of unprotected human skin. Over the years, several classic articles dealing with these topics have appeared in the literature.

2. Wind Chill

A. Central Region Technical Attachment 88-05

Joseph T. Schaefer, Director, National Weather Service Training Center, published Central Region Technical Attachment 88-5, "The Effect of Wind and Temperature on Humans", in February 1988. His work is a nice summary of some of the more important information contained in the classic articles of the last 50-odd years. The following is material extracted from Central Region Technical Attachment 88-5. Additional information has been added for clarification:

A fair question to ask is, "What exactly does the wind chill represent?"

Antarctic explorers, Paul Siple and Charles Passel, (during the Antarctic winter of 1941) measured the time required for 250 grams of water in a plastic container to freeze under various weather conditions. Not surprisingly, they found that the principal factors involved were the initial temperature of the water and the diffusion rate of heat from the container to the atmosphere. This rate is determined by the wind speed and the air temperature.

In a 1945 paper, Siple and Passel empirically related these data to the rate of heat loss of exposed human skin. They derived curves of constant heat loss as a function of temperature and wind speed by assuming that the skin temperature is maintained at 91.4°F, and not explicitly considering heat production by the body (i.e., the metabolic rate).

Their formulas show that a high temperature with fast winds can produce the same amount of cooling as a much lower temperature with nearly calm conditions. The wind chill equivalent temperature (T_{wce}), or wind chill index, is obtained from these curves. T_{wce} is defined as the theoretical temperature that would have to occur in conjunction with a 4 mph (3.48 knots) wind to produce the same amount of body cooling as is caused by the observed conditions.

B. Discussion of Wind Chill Equivalent Temperature

The wind chill tables presented in Figures 1-3 are used widely by the National Weather Service and the media. They are based on calculations of the wind chill equivalent temperature (T_{wce}). Wind speed must be 4 mph (3.48 knots) or more to use these wind chill tables.

Schlatter (1981) began with:

$$H = (10.45 + 10V^{0.5} - V)(33 - T), \quad (1)$$

H is a heat flux, that is, the rate of heat loss per unit area of exposed skin in kilocalories per square meter per hour ($\text{kcal m}^{-2} \text{h}^{-1}$). V is in units of m sec^{-1} ($1 \text{ m sec}^{-1} = 2.24 \text{ mph} = 1.94 \text{ knots}$) and T is in $^{\circ}\text{C}$. The wind chill equivalent temperature (T_{wce}) is defined as the temperature that would result in the same heat loss if the wind speed were low, say V_0 . In other words,

$$H = H_0 = (10.45 + 10V_0^{0.5} - V_0)(33 - T_{wce}).$$

The most often used value of V_0 is 1.79 m sec^{-1} (4 mph). Substituting for this value above, one obtains:

$$H_0 = 22.04(33 - T_{wce}).$$

Solving for T_{wce} , one gets:

$$T_{wce} = 33 - H_0/22.04$$

and, substituting H for H_0 with equation (1), one obtains:

$$T_{wce} = 33 - (10.45 + 10V^{0.5} - V)(33 - T)/22.04 \quad (2)$$

Equation (2) is used to derive Figure 1.

Equation (2) can be converted to equation (3):

$$T_{wce} = 91.4 - 0.04537(10.45 + 6.686V^{0.5} - 0.447V)(91.4-T)$$

where V is in units of mph and T is in °F

Equation (3) is used to derive Figure 2.

Equations (2) and (3) can also be converted to equation (4):

$$T_{wce} = 91.4 - 0.04537(10.45 + 7.172V^{0.5} - 0.514V)(91.4-T)$$

where V is in units of knots and T is in °F

Equation (4) is used to derive Figure 3.

T_{wce} is a good measure of convective cooling, the principal source of body heat loss (Ruffner and Bair, 1977).

All calculated values using T_{wce} should agree within 1°F with the values in Figures 2-3.

C. Remainder of Central Region Technical Attachment 88-05

Thus, the wind chill index (T_{wce}) is an effort to tell the public "how cold" it will seem. It gives an indication of what kind of clothes will be necessary to prevent body heat loss during outdoor activities. However, it does not really tell us when it is dangerous to be outside, i.e., when we are susceptible to frostbite.

This topic was explored by two Russian meteorologists, Adamenko and Khairullin (1972) during the winters of 1967 and 1968. They instrumented the cheeks, noses and earlobes of about 40 people whose age ranged between 19 and 35 and had them walk slowly around out of doors (for a half hour to an hour). People of both sexes were used. Experiments were conducted in four different cities with temperatures ranging from 50°F to -40°F and winds varying from calm to 29 knots. (Radiation flux on a vertical surface was negligibly small during the experiments.)

Wind Speed (M/Sec)	Air Temperature (°C)															
	6	3	0	-3	-6	-9	-12	-15	-18	-21	-24	-27	-30	-33	-36	-39
3	3	-1	-4	-7	-11	-14	-18	-21	-24	-28	-31	-34	-38	-41	-45	-48
6	-2	-6	-10	-14	-18	-22	-26	-30	-34	-38	-42	-46	-50	-54	-58	-62
9	-6	-10	-14	-18	-23	-27	-31	-36	-40	-44	-48	-53	-57	-61	-65	-70
12	-8	-12	-17	-21	-26	-30	-35	-39	-44	-48	-53	-57	-62	-66	-71	-75
15	-9	-14	-18	-23	-27	-32	-37	-41	-46	-51	-55	-60	-65	-69	-74	-79
18	-10	-14	-19	-24	-29	-33	-38	-43	-48	-52	-57	-62	-67	-71	-76	-81
21	-10	-15	-20	-25	-29	-34	-39	-44	-49	-53	-58	-63	-68	-73	-77	-82
24	-10	-15	-20	-25	-30	-35	-39	-44	-49	-54	-59	-64	-68	-73	-78	-83

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Figure 1. Wind Chill Equivalent temperatures (T_{wce}) for various air temperature (°C) and wind speed ($m sec^{-2}$) values.

Wind Speed (MPH)	Air Temperature (°F)																
	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
4	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	32	27	22	16	11	6	0	-5	-10	-15	-21	-26	-31	-36	-42	-47	-52
10	22	16	10	3	-3	-9	-15	-22	-27	-34	-40	-46	-52	-58	-64	-71	-77
15	16	9	2	-5	-11	-18	-25	-31	-38	-45	-51	-58	-65	-72	-78	-85	-92
20	12	4	-3	-10	-17	-24	-31	-39	-46	-53	-60	-67	-74	-81	-88	-95	-103
25	8	1	-7	-15	-22	-29	-36	-44	-51	-59	-66	-74	-81	-88	-96	-103	-110
30	6	-2	-10	-18	-25	-33	-41	-49	-56	-64	-71	-79	-86	-93	-101	-109	-116
35	4	-4	-12	-20	-27	-35	-43	-52	-58	-67	-74	-82	-89	-97	-105	-113	-120
40	3	-5	-13	-21	-29	-37	-45	-53	-60	-69	-76	-84	-92	-100	-107	-115	-123
45	2	-6	-14	-22	-30	-38	-46	-54	-62	-70	-78	-85	-93	-102	-109	-117	-125

Figure 2. Same as Figure 1, but for air temperature in °F and wind speed in miles per hour (mph).

Wind Speed (knots)	Air Temperature (°F)																
	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
4	33	28	23	18	13	7	2	-3	-8	-13	-18	-24	-29	-34	-39	-44	-49
5	30	25	19	14	8	3	-2	-8	-13	-19	-24	-29	-35	-40	-46	-51	-57
10	20	13	7	1	-6	-12	-18	-25	-31	-37	-44	-50	-56	-63	-69	-75	-82
15	13	6	-1	-7	-14	-21	-28	-35	-42	-49	-56	-63	-70	-77	-84	-91	-97
20	9	2	-6	-13	-20	-28	-35	-42	-50	-57	-64	-72	-79	-86	-94	-101	-108
25	6	-2	-9	-17	-25	-32	-40	-47	-55	-63	-70	-78	-85	-93	-100	-108	-116
30	4	-4	-12	-20	-28	-35	-43	-51	-59	-66	-74	-82	-90	-98	-105	-113	-121
35	2	-6	-14	-22	-30	-37	-45	-53	-61	-69	-77	-85	-93	-101	-109	-117	-125
40	1	-7	-15	-23	-31	-39	-47	-55	-63	-71	-79	-87	-95	-103	-111	-119	-127
45	1	-7	-15	-23	-31	-39	-47	-56	-64	-72	-80	-88	-96	-104	-112	-120	-128

Figure 3. Same as Figure 1, but for air temperature in °F and wind speed in knots (kt).

The temperatures of the various facial parts were found to be related to the wind and air temperature by the following least squares formulas, where T is in °F and V is in knots:

$$T_{\text{cheek}} = 0.4T - 4.3V^{0.5} + 53.4 \quad (5)$$

$$T_{\text{nose}} = 0.4T - 4.3V^{0.5} + 49.6 \quad (6)$$

$$T_{\text{ear}} = 0.4T - 4.3V^{0.5} + 40.8 \quad (7)$$

The last term in these equations arises from the amount of heat contained in the blood supplied to the various portions of the face. More blood flows to the cheek than the ear and it stays warmer. Since freezing requires the skin temperature to be 32°F or colder, these temperatures, not the more commonly given wind chill index (T_{wce}), indicate when there is a danger of frostbite.

Averaging these three equations together, gives an approximate temperature for the face after a half hour to an hour of slow walking outdoors:

$$T_{\text{face}} = 0.4T - 4.3V^{0.5} + 47.9 \quad (8)$$

For still air, the air temperature has to drop to a -39.8°F before the face temperature will reach freezing. However, for a rather light 10-knot wind, a temperature of -5.8°F (T_{wce} of -21.8°F) can cause frostbite.

It must be noted that neither the skin temperature formulas nor the wind chill formula considers either (solar) radiation or humidity. Obviously, direct sunshine provides significant heating to the body. High humidities produce cooler effective temperatures because moist air has both a greater heat capacity and a greater thermal conductivity than dry air. Thus, cold moist air is harder on the body than cold dry air. However, the moisture content of very cold air is fortunately quite small and this is typically a minor effect.

Physical fitness and personal acclimation to cold weather has very little to do with facial freezing. In fact, some of the Russian data was collected using residents of Noril'sk in north central Siberia (about 69°N) where winters are more extreme than those found in the contiguous United States. The guideline for issuing wind chill advisories when T_{wce} is -35°F or less is, in actuality, rather conservative. Freezing of exposed skin, in periods of a half hour to an hour, is a real threat even when the wind chill equivalent temperature is higher (less negative) than

the -35°F threshold. (Note: the - 35°F threshold pertains to wind chill **advisories** in the northern parts of the Central Region and the mountains of the west and wind chill **warnings** in the southern part of the Central Region.)

D. Discussion of Frostbite

The paper by Adamenko and Khairullin (1972) is the **classical** study of the freezing of unprotected human skin under combinations of wind speed and air temperature. A nomogram is presented in Figure 4. Facial skin temperature (θ_s) in °C is denoted along the y-axis. Air temperature (θ) in °C is exhibited along the x-axis. The diagonal lines represent various wind speeds in m sec⁻¹. We are also including two other versions of the nomogram. One uses units of °F and mph (Fig. 5) and the other employs °F and knots (Fig. 6). Figure 5 shows that **unprotected skin freezes**, in periods of a half hour to an hour of slow walking, at -24°F in a 4 mph wind ($T_{wce} = -24°F$) to -11°F in an 11 mph wind ($T_{wce} = -26.7°F$) to +16°F in a 36 mph wind ($T_{wce} = -15.4°F$). The higher the wind speed the faster (closer to a half hour than an hour) the skin will freeze, assuming all conditions except wind speed are equal.

The temperature values and corresponding wind chill equivalent temperatures are lower (less positive) than those given in Central Region Technical Attachment 88-5. This is because Schaefer used an average of the formulas for cheek, nose, and ear skin temperature. Although not stated explicitly, calculations from the nomogram in comparison with the equations indicate Adamenko and Khairullin used nose temperature (T_{nose}), equation 6, in developing their nomogram. For example, the +16°F in the 36 mph wind ($T_{wce} = -15.4°F$), cited above, would yield a +20°F in a 36 mph wind ($T_{wce} = -9.8°F$), using the Schaefer T_{face} equation (equation 8). Perhaps T_{nose} was chosen by the Russians because the nose is usually more difficult to protect than the cheek or ear.

Thus, $\theta_s = T_{nose} = 0.4T - 4.3V^{0.5} + 49.6 = 32$, where t is in °F and V is in knots, is the recommended formula to be used to calculate the temperature and wind speed combinations needed for the onset of frostbite ($\theta_s = 32°F$).

Returning to the example for a 10-knot wind and using the equation for T_{nose} , an air temperature of -10°F ($T_{wce} = -26.7°F$) can cause frostbite during a half hour to an hour stroll. If you are walking slowly outdoors for the same period of time with exposed earlobes in a 10-knot wind, an air temperature of +12°F ($T_{wce} = -9.4°F$) can cause frostbite based on the T_{ear} equation (Eq. 7).

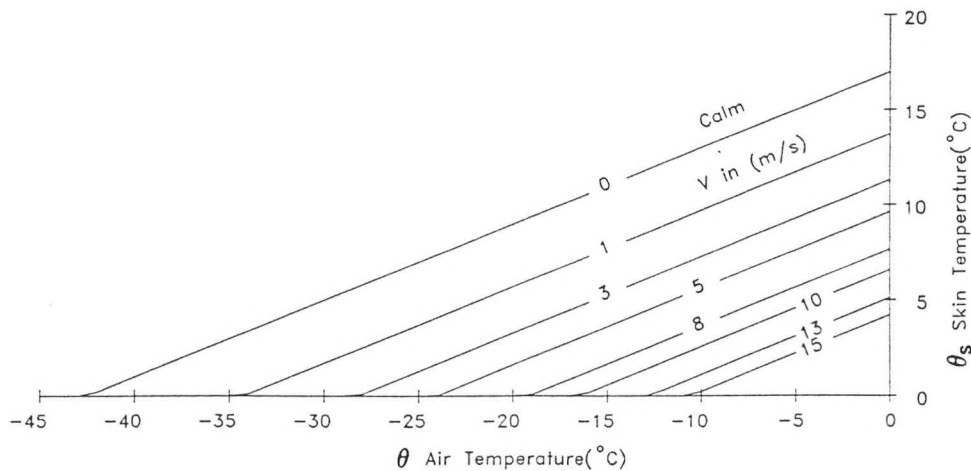


Figure 4. Nomogram for determining skin temperature of the nose from indicated air temperature (°C) and wind speed values (m sec⁻¹) after a half hour to an hour of slow walking outdoors.

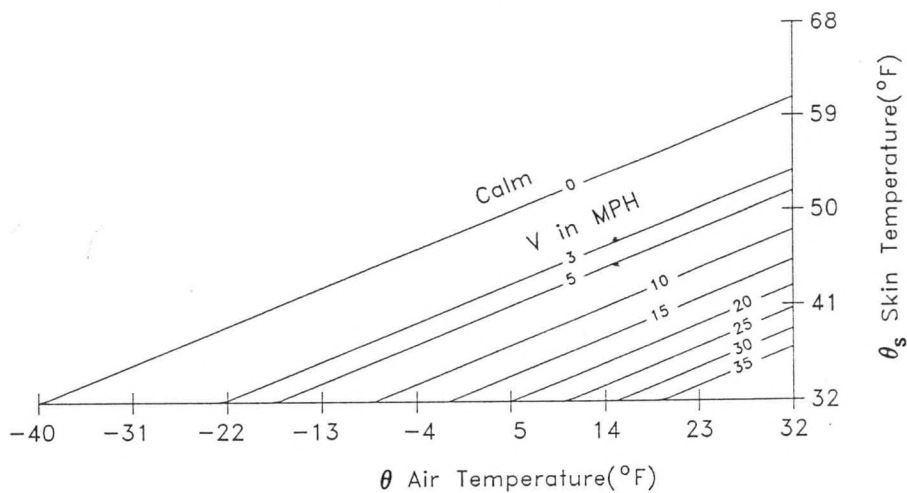


Figure 5. Same as Figure 4, but for air temperature in °F and wind speed in miles per hour (mph).

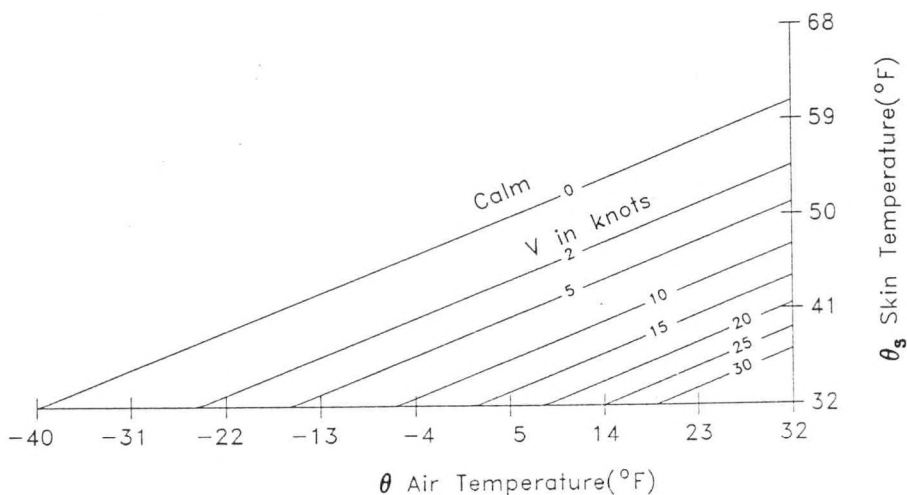


Figure 6. Same as Figure 4, but for air temperature in °F and wind speed in knots (kt).

Thus, wind chill equivalent temperatures considerably higher (less negative) than -35°F (the lower limit to wind chill warnings in the Central Region) can freeze unprotected skin.

E. Solar Radiation

We still must consider solar radiation. R. G. Steadman (1971) states in his concluding paragraph, "Hence, sunshine effectively raises the ambient temperature by approximately 14°C (25°F) under nearly calm conditions, and approximately 7°C (13°F) in a strong wind".

F. Other Effects

Speaking of wind chill equivalent temperature (T_{wce}), Schlatter (1981) states, "Although it accounts for convective heat losses due to turbulent air motion around the body, it fails to consider many other possibilities for heat retention or loss: How much clothing is worn and how well does it insulate against heat loss? Is the person jogging or sitting for hours in a football stadium? Is the sun shining (see solar radiation above)? Dark clothing absorbs solar energy efficiently. How hard is the person breathing? Inhaled air is warmed within the lungs only to be exhaled again - a significant heat loss which can amount to 20 percent or more of the total. These and other variables in the heat equation for the body are difficult to quantify,...". The paper by R.G. Steadman (1971), cited above, attempts to answer some of these questions.

3. Summary

The National Weather Service Operations Manual (WSOM) Chapter C-42, Section 4.8, Wind Chill., states in part, "No specific rules exist for determining when wind chill becomes dangerous. As a general rule, the threshold for potentially dangerous wind chill conditions is about -20°F . However, mitigating circumstances, such as strong sunshine, may require colder (less positive) threshold temperatures. Regional variations exist and different wind chill thresholds may be established at the option of the regional directors and formalized through the issuance of ROMLs. Different thresholds may exist within the same region.

According to Central Region ROML C-01-93, wind chill warnings should be issued in the northern parts of the Central Region and the mountains of the west when wind chills reach -50°F and in the southern part of the region when wind chills reach -35°F .

Wind chill advisories are issued for values 15° to 20°F warmer (less negative) than the warning thresholds.

Overall, the literature indicates that the criteria for wind chill warnings and advisories used in ROML C-01-93 are oversimplified. Theoretically, the threshold values for warnings and advisories should be higher (less negative) than the values given in ROML C-01-93. Actually, the wind chill value of -20°F, cited in WSOM Chapter C-42, is a reasonable value overall for the issuance of wind chill warnings based on the Adamenko and Khairullin data, recognizing that wind chill values higher (less negative) than -10°F can still cause frostbite on earlobes.

However, based on the Steadman study, calculated wind chill thresholds for warnings and advisories are not as severe as indicated during sunny weather, especially when winds are light. This suggests different criteria (less positive values of T_{wce}) should be used for sunny days and the standard T_{wce} for cloudy days or at night.

We at CRH are certain this material will breathe new life into your ongoing wind chill discussions.

4. Acknowledgments

I thank Dr. Thomas W. Schlatter, Environmental Research Laboratories, Forecast Systems Laboratory, Forecast Research Division, for his help in converting the wind chill equivalent temperature (T_{wce}) from metric to English units to match the values given in Figures 2-3, and for his overall review of the manuscript. I would also like to thank Dr. Joseph T. Schaefer for his helpful comments after he reviewed the original manuscript.

5. References

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